

Compact Radio Cores and Nuclear Activity in Seyfert Galaxies

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ABSTRACT

Using recent high-resolution ($<0.1''$) radio observations of a large sample of Seyfert galaxies (Roy et al., 1994), we analyze the relations between their compact radio core emission and several nuclear and host galaxy properties (galaxy morphology, optical, infrared, X-ray, extended radio emissions, interaction parameters, and some emission line properties). We apply survival analysis techniques in order to exploit the information contained in the numerous "censored" data (upper limits on fluxes).

We find that Seyfert nuclei hosted in early-type galaxies are, on average, characterized by stronger radio core emission than the norm for Seyfert galaxies. Galaxies with a nearby companion display enhanced radio core emission with respect to objects without companions. Furthermore, we confirm that Seyfert types 2 host more powerful compact radio cores than types 1.

Remarkably, radio core emission appears to be unrelated to optical, near-infrared, and far-infrared radiations, but shows some correlation with total radio emission and with tracers of nuclear activity such as the IRAS 12 and 25 μm band, hard X-ray and narrow-line emissions. This favours the view that Seyfert radio cores are typically powered by AGN rather than by radio supernovae.

A link between radio core strength and bolometric luminosity is suggested, in analogy to what is observed in the cores of radio-quiet QSOs.

Subject headings: galaxies: active – galaxies: Seyfert – galaxies: nuclei – radio continuum: galaxies

1. INTRODUCTION

Very high resolution radio observations of active galactic nuclei (AGN) can be profitably used to probe the central engine, since they are principally sensitive to nuclear non-thermal emission at high brightness temperature from AGN activity and help us to discriminate against low brightness temperature extended radio emission expected from the presence of circumnuclear HII regions. For instance, compact radio cores are fairly frequently detected in samples of Seyfert galaxies, but rarely detected in optically selected starburst galaxies (e.g., Norris et al., 1990). Consistently, the deeper, very long baseline interferometry (VLBI) survey of ultraluminous infrared (IR) galaxies by Lonsdale, Smith & Lonsdale (1993), which did not reveal any correlation between the detection of compact radio cores and the optical classification of galactic nuclei, has been used to suggest the likely existence of AGNs embedded in dust within their nuclei. The observations of compact radio cores in Seyfert galaxies have recently been also employed as a new test of the canonical unification schemes of AGNs, according to which Seyfert type 1 objects (S1) would contain the same central engines as Seyfert types 2 (S2), but would have the broad-line region (BLR) and the strong optical, UV, and X-ray continua of the central source concealed from our view by a disk or torus of dusty molecular clouds (see, e.g., the review by Antonucci, 1993). If the torus surrounding the nucleus is optically thin at radio wavelengths, orientation effects should have no effect on the radio appearance of Seyfert galaxies. As a matter of fact, contrarily to old contentions (see, e.g., the review by Lawrence, 1987) based on poor statistics, recent low-resolution radio observations show no significant differences in the major radio properties (central and total radio powers, radio size, radio spectral index) of S1 and S2 objects (e.g., Edelson, 1987; Ulvestad & Wilson, 1989; Giuricin et al., 1990), as is expected from standard unified schemes.

But, surprisingly, in the high-resolution radio survey by Roy et al. (1994) compact radio cores were found more commonly in S2 than in S1 galaxies, although the disk radio powers, $[\text{OIII}]\lambda 5007\text{\AA}$ emission line luminosities, and far-infrared (FIR) luminosities of the two classes of objects are similar (Roy et al., 1994, 1996). In order to reconcile their findings with the unified view of AGNs, the authors offered some models which resort to free-free absorption of S1 ra-

dio cores by the narrow-line region (NLR), if the radio cores lie in the BLR, or by individual NLR clouds, if the radio cores are located in the NLR.

In this paper we use Roy et al.'s (1994) radio core data set in order to examine the relations (as yet unexplored) between radio core emission and several properties of Seyfert galaxies and nuclei. Specifically, we examine the 2.3 GHz radio core fluxes F_c of the optical+infrared-selected sample of Seyfert galaxies observed by Roy et al. (1994). The authors observed 157 Seyfert galaxies with the 275 km Parkes-Tidbinbilla Interferometer (PTI) at 1.7 or 2.3 GHz. They combined fluxes (or 5σ upper limits on fluxes) from different observations, converting 1.7 GHz fluxes to 2.3 GHz with the adoption of a spectral index $n = -0.7$ ($F_\nu \propto \nu^n$). Their high-resolution survey, characterized by uniform sensitivity and resolution, is blind to Kpc-scale emission of low brightness temperature, whereas it is sensitive only to structures with brightness temperature greater than 10^5 K and sizes less than $0''.1$, which correspond to 20–200 pc over the redshift range $0.01 < z < 0.1$, typical of the sample.

Radio core data of 22 Seyfert galaxies have recently been published by Sadler et al. (1995) as part of their multifrequency (at 1.7 GHz, 2.3 GHz, 8.4 GHz) PTI survey of radio cores in a sample of nearby spiral galaxies. Their radio core fluxes appear to be in substantial agreement with Roy et al.'s (1994) for the 10 objects in common.

In this paper we restrict ourselves to Roy et al.'s (1994) 149 Seyfert galaxies having $z < 0.1$, since distant galaxies might represent a different class of objects. The radio data set considered comprises about 35% of detections and 65% of upper limits (25% and 47% of detections for S1 and S2, respectively). The presence of many upper limits on the radio fluxes dictates the use of the techniques of Survival Analysis suitable for the treatment of "censored" data (see, e.g., the review by Feigelson, 1992). In practice we use the software package ASURV (Rev 1.2, La Valley, Isobe & Feigelson, 1992) in which the methods presented in Feigelson & Nelson (1985) and in Isobe, Feigelson & Nelson (1986) are implemented. We pay particular attention to removing distance effects when we study luminosity-luminosity correlations and when we compare luminosities of subsets of objects which lie at different average distances.

Basically, we search for correlations (as yet unexplored) between the radio core emission and several properties of Seyfert nuclei and host galaxies.

These include galaxy morphology, optical, infrared, X-ray, extended radio emissions, interaction parameters and some emission-line nuclear properties. Several of these properties are indicators of nuclear activity. Our study will also ensure that the above-mentioned difference between the radio core emissions of S1 and S2 objects is not simply due to a systematic difference of the two samples in some properties, to which radio core emission might be strongly related.

In §2 we describe our statistical analysis. In some tables or plots we present the most outstanding results for the interesting cases. We shall not bother with extremely weak correlations (at the $<90\%$ significance level); correlations at a level falling between 90% and 95% will be referred to as marginal. All data compiled and results obtained are available on request. §3 summarizes our results and contains our conclusions.

2. Analysis and Results

2.1. The Radio Core Powers of Seyfert Galaxies.

The distances D of the nearby galaxies which are included in the "Nearby Galaxies Catalog" (NBG) by Tully (1988) are taken directly from the values tabulated therein; these distances are based on velocities, an adopted Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and the Virgocentric retardation model described by Tully & Shaya (1984). We use redshift-distances with the same H_0 and $q_0=0$ to calculate the monochromatic radio core powers P_c (expressed in W/Hz) of non-NBG galaxies.

We employ the Kaplan-Meier product-limit estimator (which is a part of the ASURV package) in order to calculate the median and the distribution function of the radio core power P_c . The Kaplan-Meier estimator provides an efficient, non-parametric reconstruction of information lost by censoring in the case of randomly censored data sets. This estimator redistributes the upper limits uniformly along all the intervals of lower detected values. In our case it can be applied to radio powers, whose censoring pattern tends to be randomized by the large distance interval covered by our objects. Figure 1 shows the histogram of $\log P_c$ for the 149 Seyfert galaxies. For our Seyfert sample ($N=149$ objects, with $N_{ul}=93$ upper limits) we obtain a median value of $\log P_c = 20.9$ (W/Hz), together with the 75th and 25th percentiles of 20.1 (W/Hz) and 22.0 (W/Hz). The histogram has a clear

maximum at the lowest detected powers ($\log P_c \sim 20$ (W/Hz)) and a plateau around $\log P_c = 22$ (W/Hz). The data are consistent with the presence of compact cores in all Seyfert galaxies at a level of $\log P_c \lesssim 20$ (W/Hz), which falls below the detection threshold for the nearest objects.

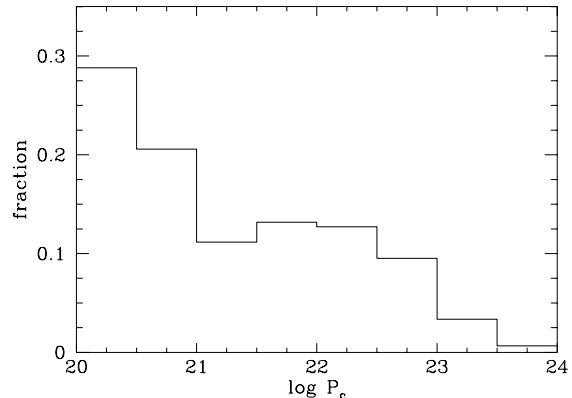


Fig. 1.— The histogram of the values of $\log P_c$ (where P_c is the radio core power in W/Hz) for all 149 Seyfert galaxies. The $\log P_c$ -distribution function is calculated by means of the Kaplan-Meier estimator.

The radio cores of Seyfert galaxies are orders of magnitude in power stronger than the radio cores of normal "quiescent" spirals (e.g., $\log P_c < 16$ W/Hz at similar frequencies for the Milky Way (Sgr A*) and for M31; see, e.g., the reviews by Lo, 1994, and by Kormendy & Richstone, 1995). They are also more powerful (by more than one order of magnitude) than the (rarely detected) radio cores of samples of nearby, non-Seyfert spirals, including objects with starburst nuclei (e.g., Colina & Pérez-Olea, 1993; Sadler et al., 1995). In particular, we note that the 25th percentile of the $\log P_c$ -distribution of Sadler et al.'s (1995) PTI core data for 29 spirals is less than 19.5 (W/Hz) at 5GHz (i.e., ~ 19.7 (W/Hz) at 2.3 GHz, for a spectral index $n=-0.7$).

The power of Seyfert radio cores is roughly comparable to that of radio cores detected in luminous IRAS galaxies, with starburst or AGN nuclear spectra (Lonsdale et al., 1993), and in many low-redshift ($z < 0.1$), optically-selected radio-quiet objects of the Bright Quasar Sample (see, e.g., Kellermann et al., 1989; Lonsdale, Smith & Lonsdale, 1995). These two surveys, having a lower sensitivity threshold, contain a lower fraction of censored fluxes than Roy et

al.’s (1994) sample.

On the other hand, a comparison with Slee et al.’s (1994) wide sample of early-type galaxies of low total radio power (denoted as subsample A by the authors) reveals that these objects typically host stronger radio cores than our Seyferts (with a Kaplan–Meier estimate of the median of $\log P_c = 21.3$ (W/Hz) at 2.3 GHz and a large percentage ($\sim 65\%$) of core detections). If the comparison is limited to subsets of nearby objects (distance $D < 100$ Mpc), this difference increases. Thus, our analysis strengthens Sadler et al.’s (1995) suggestion (based on a much smaller data set) that radio cores are more prominent in early-type than in Seyfert objects. Furthermore, their multifrequency PTI observations revealed that the radio cores detected in spiral (mostly Seyfert) galaxies usually have steep radio spectra (with a median spectral index $n = -1.0$ between 2.3 GHz and 8.4 GHz), in contrast with the flat radio spectra of Slee et al.’s (1994) early-type galaxies (median $n = +0.3$).

2.2. Radio cores and Seyfert types.

In general, we rely on the Seyfert classification given by the authors, with the exception of a few objects (NGC 2992, Tol 113, UGC 12138) which we class as S2 galaxies (NGC 2992 was classed as type 1.9 by Durret (1989) and Whittle (1992a); Tol 113 was given a subtype 1.9 by Whittle (1992a); UGC 12138 was found to be a subtype 1.8 by Osterbrock & Manti (1993)). Moreover, we consider separately Mrk 516 and Mrk 883, which are probably Seyfert/LINER transition cases (see Rudy & Rodriguez–Espinosa, 1985).

Roy et al. (1994) employed the ”difference-of-two-proportions” test with the Yates continuity correction to quantify the difference in detection rates between far-infrared (FIR)–selected S1s and S2s. Within their far-infrared (FIR)–selected sample, where the two Seyfert types have the same distance distribution, the authors found the difference to be significant to the 98.8% confidence level. The combined optical and mid-infrared (MIR)–selected sample may also show a lack of detected radio cores in S1s, but that effect may be simply explained by the fact that S1s are typically more distant than S2s.

We wish to apply the methods of survival analysis in order to evaluate the difference between the radio core emission of S1s and S2s. In this case, we wish to compare the distribution functions of a given quan-

tity (the radio core power) for two different samples of objects (S1 and S2) by testing the ”null” hypothesis that the two independent random samples are randomly drawn from the same parent population. This is accomplished by using two versions of Gehan’s test (one with permutation variance and the other with hypergeometric variance, hereafter called G_1 and G_2 , respectively), the logrank (L), the Peto-Peto (P_1) and Peto-Prentice (P_2) tests. These two-sample tests give the probability p that two samples as different as these would be drawn from one parent population. The statistical significance of the difference between the distributions of two datasets is at the $100(1 - p)\%$ level. The two-sample tests differ in how the censored points are weighted and consequently have different sensitivities and efficiencies with different distributions and censoring patterns. Since two-sample tests seek only to compare two samples rather than to determine the true underlying distribution of a given variable, they do not require that the censoring patterns of the two samples be random.

If we applied the five two-sample tests to the distributions of the radio core powers P_c of S1 and S2 objects, we would obtain only an upper limit of p (an average of $p = 0.06$), because S1s are typically more distant than S2s and, hence, tend to be brighter (or to have greater upper limits on luminosities). In order to remove this distance effect in the comparison of subsets of objects lying at different typical distances, we consider the logarithmic relation

$$\log P_c = 17.078 + \log F_{min} + 2 \log D, \quad (1)$$

which gives the minimum value of $\log P_c$ (with P_c in W/Hz) corresponding to the 5σ sensitivity threshold of $F_{min} = 3$ mJy for a detected object at luminosity distance D (in Mpc). Obviously, detections and upper limits on P_c cluster near this relation in the $\log P_c - \log D$ diagram; this diagram is illustrated in Figure 2. We use this relation, which illustrates the sensitivity threshold of the radio survey, in order to evaluate the *observed* minus *calculated* value of $\log P_c$, i.e. $\Delta(\log P_c)$, for each object. In this manner we obtain $\Delta(\log P_c)$ –distributions which are free from distance selection effects (see Figure 3). Applying the two-sample tests to the $\Delta(\log P_c)$ –distributions of S1s and S2s (with $N = 57$ S1 and $N_{ul} = 43$ upper limits; $N = 90$ S2 and $N_{ul} = 48$), we find that they differ at the average level of $p = 0.006$ ($p = 0.006$, $p = 0.006$, $p = 0.010$, $p = 0.007$, $p = 0.003$ according to the G_1 , G_2 , L , P_1 , P_2 tests, respectively). Thus, our analysis

improves the statistical significance of the difference. The $\Delta(\log P_c)$ -distributions are characterized by the medians of -0.33 and -0.15 for S1s and S2s; this suggests a typical difference of a factor of ~ 1.5 between the radio core powers of the two types of Seyferts.

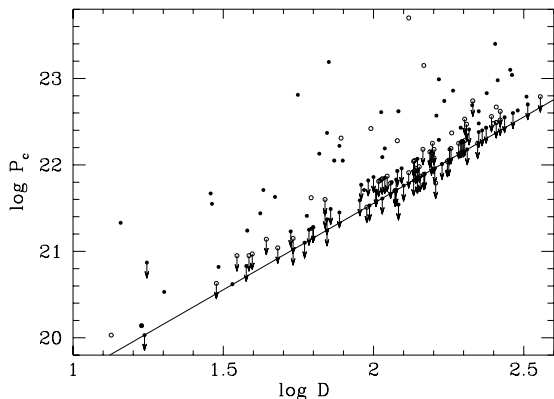


Fig. 2.— The $\log P_c$ - $\log D$ plot for 149 Seyfert galaxies; P_c is the radio core power (in W/Hz), D is the distance (in Mpc). Upper limits on P_c are indicated by arrows. Different symbols denote S1s (open circles), S2s (dots), and objects of uncertain type (crosses). The straight line given by eq. (1) in the text is shown.

Within the standard unification schemes of Seyfert galaxies, if the radio cores were located near obscuring NLR clouds, we would expect a difference of a factor two between the radio core powers of S1s and S2s, which is not too far from the difference we find. As a matter of fact, if the NLR clouds lie closer to the nucleus than do radio cores, when observing S1s along the axis of the NLR, radio emission from radio cores on the far side of the nucleus would be blocked from view by the NLR clouds with which they are associated, and so only the components on the near side would be visible in the radio. On the other side, S2s are viewed perpendicular to the axis of the NLR and so our view of the radio cores would not be obscured by the NLR clouds (see Figure 5b in Roy et al., 1994). Then the radio power of S1 cores would appear to be typically half that of S2 cores (as already suggested by Roy et al., 1994). A similar mechanism would operate if the radio cores were on the nuclear side of the NLR clouds or in a mixture of the two cases.

On the other hand, if the radio cores were located within (or near) the BLR, a large covering factor of the NLR (closer to 0.5 than to 0.01) by optically thick

clouds is required to give rise to some detectable difference in P_c between S1s and S2s. Such large covering factors disagree with the expectations of standard photoionization models of the NLR, but are consistent with recent views which take into account the presence of dust in the NLR gas; dust tends to suppress narrow line emission, which implies that photoionization models largely underestimate the covering factor (Netz & Laor, 1993).

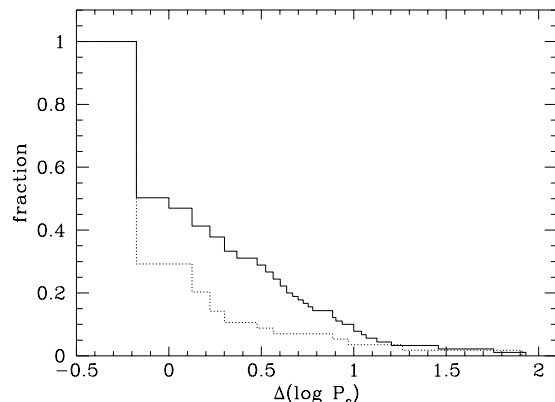


Fig. 3.— The cumulative distribution function of $\Delta(\log P_c)$ for Seyfert types 1 (dotted line) and types 2 (solid line). $\Delta(\log P_c)$ is the difference between the observed value of the logarithmic radio power and the calculated value (corresponding to the sensitivity threshold of the radio survey).

2.3. Radio cores and host galaxy morphologies.

We have taken the morphologies of Seyfert galaxies generally from Whittle (1992), the RC3 catalogue (de Vaucouleurs et al., 1991), the catalogue by Lauberts & Valentijn (1989), MacKenty (1990), Kirhakos & Steiner (1990), Vader et al. (1993), and the catalogue by Lipovetski, Neizvestny & Neizvestnaya (1987). We have simply classified our objects as E/S0 (N=31) (whenever no trace of spiral structure is observed), S (spirals) (N=72 objects, which are generally of subtypes earlier than Sbc), and S/S0 (N=4) (in a few cases of uncertain classification).

Many Seyfert galaxies, visually classified as ellipticals, are likely to be really lenticulars, since recent attempts (Zitelli et al., 1993; Granato et al., 1993; Kotilainen & Ward, 1994) to decompose Seyfert images into three major light components (bulge, disk, and

nucleus) have revealed that a disk is required in almost all cases. Many objects lack morphological classification; this is also due to the widespread presence of amorphous, disturbed and peculiar morphologies in Seyfert galaxies (e.g., Adams, 1977; MacKenty, 1990). Amorphous, very peculiar, and compact morphologies are left unclassified. Although some amorphous objects may have been inconsistently classified in the literature as E/S0, they tend to have less dominant disks than spirals (McKenty, 1990).

Applying the above-mentioned two-sample tests to the $\Delta(\log P_c)$ -distributions relative to subsets of galaxies of different morphological types, we find that compact radio cores tend to be more frequently detected in E/S0 objects than in objects having other morphologies, typically at a significance level close to 2σ . Table 1 gives the numerical outcomes, namely the total number of objects N , the number N_{ul} of upper limits on P_c , and the probabilities p that the two subsamples come from the same underlying distribution according to the application of the five two-sample tests on some subsample pairs. The effect, which indicates that E/S0 galaxies have a radio core emission that is more powerful than other objects typically by a factor of two, becomes marginally significant in subsamples of relatively nearby objects (e.g., with distance $D < 150$ Mpc), because of poorer statistics. On the other hand, in this respect no difference is observed between spirals of earlier (S0/a, Sa, Sab) and later (Sb, Sbc, Sc) subtypes.

Our finding, which is not due to different proportions of morphological types in S1 and S2 objects, reflects the presence of some radio-loud objects (e.g., 3C120, 3C327) in our sample; radio-loud objects are known to be always associated with early-type galaxies (e.g., the review by Wilson, 1992). Our result appears to be in line with the fact that in radio surveys of generic samples of bright normal galaxies, compact radio cores are more common in E and S0 galaxies than in later types (see, e. g., the review by Roberts & Haynes, 1994). Moreover, it is also consistent with the fact that generic samples of early-type galaxies show more prominent compact radio cores than Seyfert objects (see end of §2.1).

2.4. Radio cores and optical emission.

Searching for correlations between the radio core emission and the galaxy optical luminosity, we analyzed the correlation between the radio core logarithmic fluxes $\log F_c$ and the corrected total blue magni-

tudes B_T^0 , as well as the correlation between the corresponding values of $\log P_c$ and absolute magnitude M_B .

In general, we take B_T^0 directly from the RC3 catalogue. If it is not available there, we take the uncorrected B_T magnitudes from Lauberts & Valentijn (1989), Whittle (1992a), Heisler & Vader (1994); for Mk 291 and Mk 841 we take the B magnitudes derived by MacKenty (1990) for 30 kpc metric apertures (which are much greater than the galaxy sizes corresponding to the isophotal diameters at the 25 mag/arcsec²). We evaluate the total magnitudes of 3C120 and Fairall 49 by simply summing up the non-stellar nuclear component and the galaxy component as separately estimated by Kotilainen & Ward (1994). We correct these B_T magnitudes for Galactic absorption, internal absorption, and K dimming using the precepts given in RC3. Of the three corrections, the K-dimming correction is least important, whereas the corrections for internal absorption and Galactic absorption are typically about equally important in spiral objects. In cases of unknown morphological type we assume a Sa spiral morphology (T=1 according to the RC3 code), since most Seyfert galaxies are early-type spirals. We also take the B_T magnitudes (corrected for Galactic absorption and K-dimming) as derived by Heisler & Vader (1994) for a few objects in common with our list.

In general, we analyze the significance of the correlations between two "uncensored" variables by computing the two non-parametric rank coefficients, Spearman's r_s and Kendall's r_k (see, e.g., Kendall & Stuart, 1977). In our case at least one variable (F_c or P_c) is censored. In testing the significance of correlations between the variables x and y containing censored data, we evaluate the probability p that the two variables are independent, relying on the Cox proportional hazard model (which allows censored data for only one variable), on the generalized Kendall rank correlation statistics, and on the generalized Spearman rank order correlation coefficient. The last two methods also allow simultaneous censoring in both variables, but Spearman's is known to be inaccurate for small samples ($N < 30$). These three correlation tests are hereafter referred to as C , K , S , respectively. These correlation tests do not strictly require that the censored points be randomly distributed, but perform better if the censored points are not localized in a particular quadrant of the xy plane. In several cases, for simplicity's sake we shall mention only the

mean probability p which results from the application of the three correlation tests.

In order to examine the relationship between the radio core emission and emissions in other wavebands, we shall deal with correlations both between fluxes and between luminosities. Flux–flux plots will reveal the intrinsic relationship between luminosities under limited circumstances (in the case of uncensored data and linear relationship). Therefore, we will study also luminosity–luminosity correlations, but we will keep in mind that the use of luminosities instead of fluxes tends to introduce a distance bias to the data, as luminosities are correlated with distances in flux–limited samples. In the case of significant total luminosity–luminosity correlations, we shall attempt to estimate the influence of the distance effect on the correlations between luminosities in order to draw reliable conclusions on the existence of a physical relationship between emissions in two wavebands.

Basically, we shall do this by applying the new test for partial correlation in the presence of censored data (hereafter *AS* test) developed by Akritas & Siebert (1995), who have extended to censored data the concept of Kendall’s partial rank correlation with uncensored data (e.g., Siegel, 1956). The resulting partial correlation coefficient gives a measure of the correlation between two data sets (e.g., luminosities in two wavebands, in our case) independently of their correlation with a third data set (the galaxy distances, in our case). Thus, the *AS* partial correlation test is a good approach to free the luminosity–luminosity correlation of the individual luminosity–distance correlations. We use the *AS* test also for partial correlation analysis of uncensored data sets.

Applying the C , K , S correlation tests, we find no significant $\log F_c - B_T^0$ correlations for S1 ($N=39$, $N_{ul}=27$), S2 ($N=51$, $N_{ul}=25$), and all objects ($N=92$, $N_{ul}=54$). The study of the $\log P_c - M_B$ total relation confirms the absence of a total correlation for S2s, but yields a fairly strong total correlation for S1s (with a mean $p = 0.02$) together with a marginal correlation for the whole sample (with a mean $p = 0.08$). In order to explore whether these two correlations can be totally induced by a distance bias we apply the *AS* partial correlation test to the $\log P_c - M_B$ relation. We find no significant partial correlation between $\log P_c$ and M_B , which means that the total correlation between the two quantities is simply an artifact of the distance bias.

In order to verify this conclusion, we have taken

the homogeneous (albeit not very accurate) set of total V magnitudes (corrected for foreground extinction and galaxy inclination) as estimated by De Grijp et al. (1992) for the objects common to their sample. Again, we find no significant $\log F_c - V$ correlation for S1 ($N=30$, $N_{ul}=23$), S2 ($N=65$, $N_{ul}=34$), and all objects ($N=95$, $N_{ul}=47$), but a correlation between intrinsic luminosities ($\log P_c$ and M_V) for S2s (with a mean $p = 0.03$) and for all objects (mean $p = 0.04$). By applying the *AS* test we verify again that these total correlations are simply spurious distance effects.

For the S2 galaxies, which generally have a small non-stellar (nuclear) light component, we can further try to estimate the bulge magnitude simply by subtracting the contribution of disk emission. We have given a rough estimate of the disk contribution by relying on the empirical mean relation between the bulge-to-disk light ratio and the morphological type as determined by Simien & de Vaucouleurs (1986) from bulge/disk decomposition of nearly one hundred galaxies. Their sample contains several Seyfert galaxies and these do not deviate systematically from the mean relation. Explicit bulge/disk light decompositions have not been used, since the scatter in the bulge-to-disk light ratio versus morphological type is mainly due to errors in photometric decomposition (see, e. g., Giuricin et al., 1995a). According to the mean relation derived by Simien & de Vaucouleurs (1986), we adopt the following conversion Δm (in magnitude) from bulge+disk magnitudes to bulge magnitudes as a function of the Hubble morphological stage T (coded as in RC3): 0 mag for ellipticals, 0.47 mag for $T=-3$, 0.61 for $T=-2$, 0.73 for $T=-1$, 0.86 for $T=0$, 1.02 for $T=1$ (Sa), 1.23 for $T=2$, 1.54 for $T=3$ (Sb), 1.97 for $T=4$, 2.54 for $T=5$ (Sc); we adopt $\Delta m=0.6$ for generic S0, $\Delta m=0.5$ for E/S0 objects, $\Delta m=1.0$ for generic spirals or for objects with unknown morphology. For S2 objects with available B_T ($N=51$, $N_{ul}=25$) or available V ($N=65$, $N_{ul}=34$), we find that F_c is unrelated to the apparent magnitude of the bulge. Also P_c is unrelated to the absolute magnitude of the bulge, when the distance effect is removed.

We also wish to explore the relation between the radio core emission and the non-stellar optical B, V, R magnitudes evaluated by some authors through a subtraction of the host galaxy stellar component, whose contribution is important even in small nuclear apertures for S1 objects. In the choice of data we give preference to the CCD imaging studies by Granato et

al. (1993) for an optically-selected (mostly UV-excess selected) sample of S1 and those by Kotilainen, Ward & Williger (1993) for a hard X-ray selected sample (see also Kotilainen & Ward, 1994). In case of several entries for one object we take the average of the fluxes. Granato et al. (1993) listed magnitudes corrected for Galactic absorption. We correct Kotilainen et al.'s (1993) nuclear magnitudes for Galactic absorption as in RC3, for a standard extinction law ($A_V = 0.75A_B$; $A_R = 0.74A_V$). There are $N=25$ objects (with $N_{ul}=15$ upper limits on F_c) with known non-stellar B magnitudes in our sample ($N=26$ with $N_{ul}=16$ for the V and R data). They are mostly S1 objects.

For S1 and all objects, we detect neither significant correlations between F_c and the apparent nuclear magnitudes (in all three bands) nor significant partial correlations between P_c and the corresponding absolute nuclear magnitudes. This result does not change if we add a few nuclear magnitudes (corrected for Galactic absorption) that we derived from crude estimates of magnitudes or fluxes available in the literature (B=15.6 for Mk 1148 (Smith et al., 1986), R=15.6 for MCG-6-30-15 (McAlary & Rieke, 1988), B=14.4 for II Zw 136 (Smith et al., 1986)).

For $N=25$ objects ($N_{ul}=14$) with known B_T^0 and non-stellar B magnitudes, we can first subtract the non-stellar contributions from the total emission in blue light and then the disk contribution obtained by means of the above-mentioned Δm -values. These objects are mostly S1s ($N=20$, $N_{ul}=12$). Again, F_c and P_c turn out to be unrelated to their total and disk stellar emissions. The addition of a few S2s with available non-stellar B magnitudes leads to a significant P_c -absolute magnitude correlation, which can be simply explained by a selection effect (for a given total luminosity, S2s, hosting much fainter optical nuclei, have brighter bulge and disk luminosities than S1s).

We conclude that the radio core emission is unrelated to the total optical luminosity of the host galaxy, to the total and bulge stellar luminosity and to the non-stellar nuclear luminosity. We have verified that this holds true no matter whether we remove E/S0 galaxies from all samples or whether we restrict ourselves to uncensored radio data only.

Thus, in Seyfert galaxies the behaviour of radio core emission clearly differs from that of total radio emission and that of central radio emission (coming from areas of a few arcsecs in size); both emissions appear to be related to the total optical luminosity

(e.g., Edelson, 1987) and especially to the bulge optical luminosity (e.g., Whittle, 1992c).

It is interesting to note that also the compact (<0.03 arcsec) radio cores detected at 2.3 and 8.4 GHz with the Parkes-Tidbinbilla Interferometer in generic samples of early-type galaxies (Slee et al., 1994) are unrelated to the M_B absolute magnitudes. We have checked this by applying the AS correlation test to the radio core powers (interpolated at 5 GHz) and M_B -values, as tabulated by Slee et al. (1994), for their subsets of galaxies of low and high radio power ($N=62$, $N_{ul}=19$ and $N=85$, $N_{ul}=25$, respectively).

Our result appears to be particularly robust for the total optical luminosity (because of the fairly large data sample) and less reliable for the non-stellar nuclear light, because of small-number statistics. If we want to regard Seyfert nuclei simply as scaled-down versions of quasars, we would expect a radio-optical correlation such as that noted by Lonsdale et al. (1995) for the fairly compact radio structures detected by Kellermann et al. (1989) in their 5 GHz VLA survey of the Bright Quasar Sample (at $\sim 0.5''$ and $\sim 18''$ resolutions). However, by applying the AS correlation test to the luminosities tabulated by Lonsdale et al. (1995), we find that the optical-radio core correlation is not statistically significant for the subsample ($N=23$, $N_{ul}=7$) of low-redshift ($z \leq 0.10$) objects. One has to almost double the number of objects (increasing the limiting z -value up to $z \sim 0.2$) in order to reach a significant correlation at a $\geq 2\sigma$ level. But the compact radio sources detected in distant quasars can hardly be compared to our Seyfert radio cores, which have physical sizes smaller by one order of magnitude (or more).

2.5. Radio cores and near-infrared emission.

We have explored the relations between the radio core emission and the non-stellar (nuclear) near-infrared (NIR) J, H, K magnitudes. We took these magnitudes directly from the results of the NIR (K-band) imaging studies (complemented by NIR photometry) of Zitelli et al. (1993) and Danese et al. (1992), from the NIR imaging observations carried out by Kotilainen et al. (1992a, b), Kotilainen & Prieto (1995), and from the K imaging of the spectroscopically-selected CfA Seyferts by McLeod & Rieke (1995), in order of preference. These observations allowed the authors to separate the nuclear light from the stellar emission of the host galaxy. For $N=28$, 27, 34 objects (with $N_{ul}=17$, 16, 21) -mostly

S1 - we notice marginal correlations between F_c and the apparent NIR magnitudes (for all objects, not for S1s alone) together with no partial correlations between P_c and absolute NIR magnitudes.

Spinoglio et al. (1995) have estimated total near-infrared magnitudes for 27 Seyfert objects in common with our list. For S2s the authors used RC3 growth curves to extrapolate from measures obtained in the largest apertures to the total flux (as done for non-Seyfert galaxies), but only when the largest apertures are so large that the nuclear component no longer affects the shape of the growth curve. For S1s, whose NIR light is much more strongly concentrated than any of the normal galaxy growth curves, they used the galaxy/nucleus decompositions mentioned in the last paragraph and summed up these two components to obtain the total NIR flux. We used the latter approach to obtain the total flux in the K band for another 19 Seyfert galaxies (not included in Spinoglio et al., 1995) with available galaxy/nucleus decompositions. For a total of 23 S1s ($N_{ul}=13$), 23 S2s ($N_{ul}=10$), and S1+S2, we do not find any correlation between core radio flux (luminosity) and total K-band flux (luminosity).

In conclusion, the radio core emission is unrelated to the total and non-stellar nuclear NIR emissions. This holds true whether we drop out E/S0 galaxies and or retain detected objects only. As in the case of the optical-radio correlation discussed in the previous subsection, our result is more reliable for the total than for the nuclear NIR luminosity, for which statistics are poor.

2.6. Radio cores and mid-, far-infrared emissions.

Mid-infrared (MIR) emission from Seyfert nuclei is substantially due to non-stellar radiation. Nuclear radiation predominates in the small-beam MIR measures and also in the large-beam IRAS MIR data, whereas the bulk of the IRAS far-infrared (FIR) radiation is contributed by the emission of galaxy disks (e. g., Rodriguez-Espinosa, Rudy & Jones, 1987; Giuricin et al., 1995b). Consulting basically the compilation by Giuricin et al. (1995b) and the new observations by Maiolino et al. (1995), we have gathered together ground-based small-aperture ($\lesssim 10''$) measures in the standard N band ($\lambda \sim 10\mu\text{m}$). We have also collected IRAS MIR (at $\lambda \sim 12\mu\text{m}$ and $\sim 25\mu\text{m}$) and FIR (at $\lambda \sim 60\mu\text{m}$ and $\lambda \sim 100\mu\text{m}$) measures, giving preference to reference sources which report co-

added survey data (e. g., Rush, Malkan & Spinoglio, 1993; de Grijp et al., 1992; Mazzarella, Bothun & Boroson, 1991; Sanders et al., 1989; Hill, Becklin & Wynn-Williams, 1988; Helou et al., 1988) and sensitive pointed observations (Edelson & Malkan, 1986) over catalogues which report IRAS point source fluxes (e. g., Fullmer & Lonsdale, 1989). The consultation of the "Catalog of Infrared Observations" by Gezari et al. (1993) has been of valuable aid in compiling infrared data from the literature.

We find that F_c is positively correlated with the fluxes in the N band and in four IRAS bands (hereafter F_N , F_{12} , F_{25} , F_{60} , F_{100}) for all objects and for S2s because of the censoring pattern of the F_c -values of S2s (censored values of F_c cluster in the region of low infrared fluxes). However, the application of the AS test to the luminosity-luminosity diagrams, indicates that P_c correlates fairly well with the (monochromatic) luminosities L_{12} (at the $\sim 98\%$ significance level) and marginally with L_{25} , for all objects. If S1s and S2s are analyzed separately, we still find marginal $\log P_c - \log L_{12}$ correlations for S1s and S2s together with a moderate $\log P_c - \log L_{25}$ correlation (at the $\sim 95\%$ level) for S2s. Moreover, whenever we restrict ourselves to objects detected both at radio and infrared wavelengths, we still detect partial luminosity-luminosity correlations for L_{12} ($N=41$, $\sim 95\%$ level) and for L_{25} ($N=55$, 99.7% level). There are no partial luminosity-luminosity correlations in the other wavebands (not even in the case of uncensored data only).

Furthermore, we explore possible correlations of radio core emission with the IRAS colours F_{12}/F_{25} , F_{12}/F_{60} , F_{25}/F_{60} , F_{60}/F_{100} , omitting some galaxies which are undetected in two adjacent IRAS bands. F_c does not correlate with the IRAS colours, whereas P_c shows significant positive total correlations with the ratios F_{12}/F_{60} , F_{25}/F_{60} , and F_{60}/F_{100} . However, by applying the AS test (with the distance taken as the third variable) we have verified that the latter correlation is totally induced by the fact that distant and MIR-bright objects tend to have greater F_{60}/F_{100} -values (see, e.g., Giuricin et al., 1995b). On the other hand, we found that the relations $\log P_c - \log(F_{12}/F_{60})$ and $\log P_c - \log(F_{25}/F_{60})$ are not entirely induced by the positive relations between MIR luminosity and F_{MIR}/F_{FIR} colours, which are ascribed to a decreasing relative contribution of the cool emission from galaxy disks in high-luminosity AGNs (Giuricin et al., 1995b); even when the distance effect is re-

moved, they remain significant (to the 98% and 97% confidence level, respectively, for all objects). In particular the partial $\log P_c - \log(F_{12}/\log F_{60})$ correlation is significant even for uncensored data only ($N=54$, $>99.9\%$ level). The two correlations are consistent with the fact that P_c is related to L_{12} and L_{25} , but not to L_{60} .

Table 2 presents some results relative to the correlations between radio core power and infrared luminosity or colour, i.e. the total number of objects (N), the number of upper limits on F_c (N_{ul}), the number of upper limits on the infrared quantity (N'_{ul}), the partial Kendall's τ correlation coefficient, the square root of the calculated variance, σ , and the associated probability p of erroneously rejecting the null hypothesis (i.e., no correlation) (see Akritas & Siebert, 1995). Figure 4 shows the $\log P_c - \log L_{12}$ plot.

We conclude that radio core emission tends to increase with MIR emission (which is essentially a property of the nuclear source) and with the flattening of the FIR to MIR energy distribution, whilst it is unrelated to the FIR emission (which comes mostly from the host galaxy). The absence of correlations between P_c and N-band infrared luminosity might be due to small-number statistics.

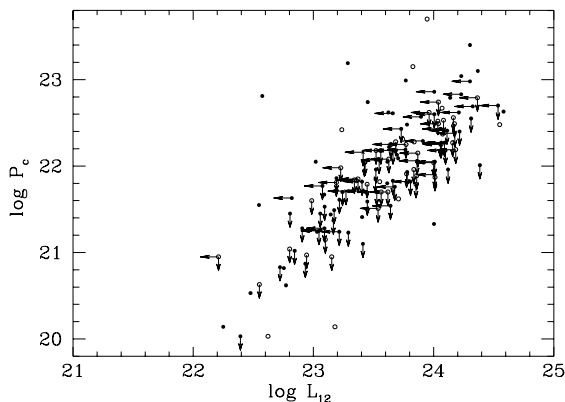


Fig. 4.— The $\log P_c - \log L_{12}$ plot, where P_c is the radio core power (in W/Hz), L_{12} is the IRAS $12\mu\text{m}$ luminosity (expressed in W/Hz). Symbols as in Figure 2.

Incidentally, Seyfert galaxies show a relation between the central N-band emission and the (total and extended central) radio emission (e.g., Ulvestad, 1986; Telesco, 1988); besides they appear to lie on the same tight FIR–total radio correlation as normal spi-

ral, ultraluminous infrared galaxies, and radio-quiet quasars (e.g., Sopp & Alexander, 1991).

2.7. Radio cores and X-ray emission.

We wish to investigate the relation between the radio core emission and the soft and hard X-ray emissions coming from various X-ray surveys. In the case of multiple entries for a galaxy, we adopt the mean values of the X-ray fluxes F_x published in a reference source. We choose unabsorbed fluxes if available, although in some cases (e.g. NGC 1068) standard corrections for flux absorption are inadequate.

The first sample of soft X-ray fluxes (in the 0.5–4.5 keV band) is based on the large compilation by Green, Anderson & Ward (1992). These authors compiled the IR and X-ray luminosities of a large sample of normal galaxies, starburst galaxies, and AGNs, observed with both the *Einstein Observatory* and IRAS satellites. Almost all the X-ray measures were taken with the Imaging Proportional Counter (IPC) aboard the *Einstein Observatory* satellite, although a few were obtained with the High Resolution Imager (HRI). The authors converted published X-ray luminosities to the chosen bandpass (0.5–4.5 keV), when necessary, and they used published fluxes obtained from X-ray spectral fits, when available. From the tabulated luminosities (corrected for Galactic absorption) and redshifts, we estimated the X-ray fluxes F_x (or upper limits) for 37 Seyferts (mostly S1) in common with our sample (with $N_{ul}=20$ upper limits on F_c and $N'_{ul} = 1$ upper limit on F_x).

Furthermore, we consider a second sample of soft X-ray data (*Einstein Observatory* IPC fluxes) which include the unabsorbed X-ray fluxes (in the 0.2–4 keV band) derived by Kruper, Urry & Canizares (1990) for 27 Seyferts (mostly S1) in common (with $N_{ul}=15$) together with the X-ray fluxes (in the same band) or upper limits derived by Fabbiano, Kim & Trinchieri (1992) for another 5 Seyferts (with $N_{ul}=2, N'_{ul}=2$).

The third sample of soft X-ray data comprises the *Einstein Observatory* IPC fluxes (in the 0.16–3.5 keV) derived by Wilkes et al. (1994) for 20 S1 objects in common (with $N_{ul}=14$).

Two sets of 2 keV fluxes were derived by Walter & Fink (1993) from the spectral analysis of the soft (0.1–2.4 keV) spectra of Seyferts detected with the PSPC detector aboard ROSAT. They described the spectra in two manners, namely using a hard X-ray power-law component, a low energy absorption, both with

and without the addition of a soft X-ray component represented by a thermal bremsstrahlung model. In both cases the 2 keV fluxes are mainly contributed by the hard X-ray power-law component. There are $N=15$ ($N_{ul}=10$) objects in common.

The ROSAT All Sky Survey of IRAS galaxies (Boller et al., 1992) provides a fifth sample of 19 objects (with $N_{ul}=13$) detected with the PSPC detector. We considered the tabulated fluxes in the 0.1–2.4 keV energy band.

Lastly, we construct a combined sample of soft X-ray data, taking the 1 keV fluxes (corrected for absorption) as reported in the catalog of X-ray spectra of AGNs by Malaguti, Bassani & Caroli (1994) for 44 objects ($N_{ul}=30$) detected with the IPC or SSS detectors aboard *Einstein Observatory* and with the PSPC instrument aboard ROSAT. In the case of multiple entries for a galaxy we adopt the mean value of F_x .

For the six samples of soft X-ray data, we found generally no flux–flux ($F_c - F_x$) correlations (except for the last sample). For S1 and all objects, we never notice partial luminosity–luminosity ($P_c - L_x$) correlations (although the 14 uncensored data of the last sample correlate at the $\sim 98\%$ significance level).

Let us turn to higher–energies X-rays, which, as compared to soft X-rays, suffer less attenuation by interstellar matter and are better indicators of AGN emission (on energy and rapid variability grounds). Short- and long-term hard X-ray variability is a common phenomenon in AGNs, but the fluxes do not generally vary by more than a factor of two (see, e.g., Grandi et al., 1992).

The HEAO1-A1 (~ 2 –20 keV) sample of identified AGNs, the so-called LMA sample studied by Grossan (1992) has $N=18$ objects (with $N_{ul}=11$) in common. We took the 5 keV fluxes as derived by Grossan (1992).

The GINGA (~ 2 –10 keV) sample of AGNs has $N=16$ objects (with $N_{ul}=6$) in common. We took the 2–10 keV fluxes mostly from Nandra & Pounds (1994) and from Williams et al. (1992) for II Zw 136, Awaki et al. (1991) for IRAS 15091–2107 and Fairall 49, Koyama et al. (1989) for NGC 1068.

The EXOSAT X-ray spectra of detected AGNs analyzed by Turner & Pounds (1989) provide a set of hard X-ray (2–10 keV) fluxes for 17 objects in common, to which we add the EXOSAT data of Mk 841 and II Zw 136 (Saxton et al., 1993), ESO12–

G21 (Ghosh & Soundararajaperumal, 1992), Mk 1148 (Singh, Rao & Vahia, 1991), Mk 618 (Rao, Singh & Vahia, 1992), IRAS 12495–1308 and IRAS 15091–2107 (Ward et al., 1988), Mk 705 (Comastri et al., 1992).

Of the above–mentioned X-ray data samples, which yield no $F_c - F_x$ correlations, only the widest one, the EXOSAT sample ($N=25$, $N_{ul}=14$), shows a weak partial, luminosity–luminosity ($P_c - L_x$) correlation (at the 94.5% confidence level).

Lastly, we construct a combined sample of hard X-ray broad-band fluxes by adding to the EXOSAT sample the GINGA 2–10 keV fluxes of Fairall 49 (Awaki et al., 1991), the *Einstein Observatory* MPC 2–10 keV fluxes (or upper limits) of NGC 1566, NGC 4235, Mk 541 derived by Halpern (1982), the ASCA GIS+SIS estimated flux of NGC 5252 in the 2–10 keV band (Cappi et al., 1995).

This combined sample ($N=30$, $N_{ul}=17$, $N_{ul}=2$) confirms the presence of a partial $P_c - L_x$ correlation, at the 97.9% confidence level (see Table 3) for all objects (of which $N=13$ objects with uncensored data correlate at a similar level of statistical significance). Figure 5 shows the $\log P_c - \log L_x$ plot.

To sum up, there is no sure evidence that the radio core emission is related to the soft X-ray emission. But we can say that it is likely to be related to the hard X-ray emission, since this comes out in the widest relevant data samples.

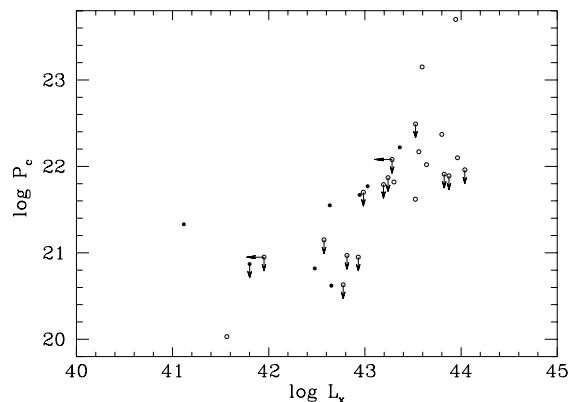


Fig. 5.— The $\log P_c - \log L_x$ plot, where P_c is the radio core power (in W/Hz), L_x is the X-ray luminosity (expressed in erg/s) in the ~ 2 –10 keV energy band. Symbols as in Figure 2.

Incidentally, several studies have established a correlation between X-ray emission and radio emission in AGNs. Radio-loud AGNs (quasars and Seyferts) are generally believed to be stronger X-ray emitters than their radio-quiet counterparts (e. g., Worrall et al., 1987; Unger et al., 1987; Kruper et al., 1990) and the proportion of radio-loud AGNs appears to increase with X-ray luminosities (Della Ceca et al., 1994). Furthermore, the soft X-ray spectral slopes show some dependence on radio power in quasars (e.g., Wilkes & Elvis, 1987; Baker, Hunstead & Brinkmann, 1995).

2.8. Radio cores and extended radio emission.

In order to explore the relation between the radio core emission and the total radio emission of Seyfert galaxies, we compile published total radio fluxes giving preference to observations made at lower resolution and at frequencies close to 2.3 GHz. According to Edelson's (1987) estimates, the total radio emission of Seyfert galaxies includes at least a $\sim 20\%$ contribution from the disk of the underlying galaxy. We take the total fluxes F_T of detected Seyfert galaxies from Wright (1974), Wilson & Meurs (1982), Gioia et al. (1983), Tovmassian et al. (1984), Ulvestad & Wilson (1984a,b), Unger et al. (1986, 1987), Harnett (1987), Burns et al. (1987), Edelson (1987), Condon (1987), Antonucci & Barvainis (1988), Ulvestad & Wilson (1989), Kellermann et al. (1989), Unger et al. (1989), Condon et al. (1990), Condon & Broderick (1991), Klein, Weiland & Brinks (1991), Gregory & Condon (1991), van Driel, van den Broek & de Jong (1991), Neff & Hutchings (1992), White & Becker (1992), Cram, North & Savage (1992), Miller, Rawlings & Saunders (1993), Vader et al. (1993), Slee et al. (1994), Gregorini et al. (1994), Bica et al. (1995). We converted the fluxes measured at different frequencies (mostly at ~ 1.4 GHz and ~ 5 GHz) to 2.3 GHz with the adoption of a spectral index $n = -0.7$.

We find total radio flux data for $N=92$ objects (with $N_{ul}=55$ upper limits on F_c and $N'_{ul}=13$ upper limits on F_T). As expected, for objects with detected radio cores, the total radio flux F_T converted to 2.3 GHz is in general, within the errors, not smaller than the radio core flux F_c , with the notable exception of Mk 841, for which Roy et al. (1994) listed a radio core flux ($F_c=55$ mJy) much greater than the total flux measured by Kellermann et al. (1989) with the VLA in the D configuration at 5 GHz ($F_T=1.5$ mJy). Moreover, in 15 cases, "censored" or "uncen-

sored" values of F_T are smaller than the corresponding "censored" values of F_c , mostly because of the limited sensitivity of Roy et al.'s (1994) survey.

Wondering how much of the total radio flux comes from the compact radio core itself, we calculate the Kaplan–Meier distribution of $\log(P_c/P_T)$ for objects with detected F_T . The distribution function of $\log(P_c/P_T)$ has a median of -0.76, together with 75th and 25th percentiles of -1.49 and -0.41. The medians are -0.90 and -0.73 for S1s and S2s, respectively, but they are not statistically different (because of small-number statistics). We have checked that the median and the two percentiles do not change appreciably if we replace some unreasonable, positive values of that quantity (see previous paragraph) with zero. Hence, we can say that the compact cores contribute, on average, a relatively small fraction ($\sim 17\%$) of the total radio emission in Seyfert galaxies.

We have verified that greater fractions ($\sim 22\%$ and $\sim 56\%$) are contributed by the compact cores observed in Slee et al.'s (1994) low-power sample of early-type galaxies (at similar resolution) and by those observed in Lonsdale et al.'s (1995) QSO sample (at lower resolution). The corresponding median contribution is smaller ($\sim 5\%$) in Lonsdale et al.'s (1993) VLBI experiment, which has, however, higher sensitivity than Roy et al.'s (1994) survey. The median contribution is even smaller ($\sim 1\%$) in Sadler et al.'s (1995) sample of non-Seyfert spirals (observed at similar resolution and sensitivity).

At first glance, there seems to be no significant partial correlation between the radio luminosities P_c and P_T corresponding to the nominal values of F_c and F_T , in spite of the correlations between fluxes and between uncensored values. But we have recognized that this apparent negative result is essentially due to the presence of several (15) cases in which a fairly high "censored" value of P_c is accompanied by a lower, "censored" or "uncensored" value of P_T . If we reasonably set the "censored" value of P_c equal to the corresponding value of P_T in all these 15 cases, we find a significant partial P_c – P_T correlation, at the $\sim 96\%$ level, for S2 and all objects. Table 4 lists the relevant results (symbols as in Table 2). Subtracting the core flux from the total radio flux, we can perform a similar analysis of the correlation between P_c and $(P_T - P_c)$. In this case, when P_c is censored, we simply take an upper limit of $(P_T - P_c)$ equal to the corresponding value of P_T . We find that P_c is related also to the extended radio power $(P_T - P_c)$.

Our result is consistent with what is observed in many samples, which, being less heavily censored, generally show a good correlation between radio core and total emissions (e.g. Slee et al.'s (1994) early-type galaxies, Lonsdale et al.'s (1995) QSOs, Neff & Hutchings' (1992) luminous IRAS galaxies), in agreement with results concerning powerful radio galaxies (e. g., Fabbiano et al., 1984). On the other side, there is no such correlation within Lonsdale et al.'s (1993) luminous IRAS galaxies and Sadler et al.'s (1995) heavily censored sample of non-Seyfert spirals.

In order to calculate the linear regression line in the case of censored data, we use Schmitt's method (e.g., Isobe et al., 1986), which works even when censoring is present in both variables. We found $P_c \propto P_T^{1.0 \pm 0.1}$ for all objects ($P_c \propto P_T^{0.9 \pm 0.1}$ for S1s and $P_c \propto P_T^{1.1 \pm 0.1}$ for S2s). If we drop out the "censored" values of P_T and repeat the linear regression analysis using also the parametric and non-parametric EM algorithms, which work only when only one variable is "censored", we confirm the above-mentioned result. The value of the slope we find is intermediate between the steep slope (1.9 ± 0.7) found by Sadler et al. (1995) for their spiral sample and the typical value (0.7) for high- and low-radio power early-type galaxies (e.g., Slee et al., 1994). However, if we repeat the linear regression analysis for E/S0 Seyferts only ($N=20$ with $N_{ul}=9$, $N'_{ul}=1$), we find a slope of 0.8 ± 0.2 , which is consistent with the value of 0.7 mentioned above.

We have inspected the characteristics of the inner radio structure on arcsec- or subarcsec-angular scale for 59 objects, for which relevant information is available in the literature (i.e., in the references already cited in this subsection and in Norris (1988), Wilson & Tsvetanov (1994), Kukula et al. (1995)). We have found that P_c is unrelated to the morphologies of the inner radio structures classified as linear, diffuse, slightly resolved, unresolved, according to the classification introduced by Ulvestad & Wilson (1984a).

Moreover, there are 35 objects for which high-resolution ($<1''$) MERLIN and mostly VLA published observations have detected an unresolved nuclear component (with a radio size ranging from $\lesssim 0.8''$ to $\lesssim 0.1''$), which is often embedded in a diffuse component or is a part of multiple and elongated structures. Converting the powers of these nuclear radio components (hereafter P_n), mostly measured at 5 GHz, to 2.3 GHz (with the adopted $n=-0.7$), we evaluate the Kaplan-Meier $\log(P_c/P_n)$ -distribution (with $N=35$, $N'_{ul}=16$). We derive a mean of -0.20 ± 0.10 ,

a median of -0.26, and a 75th (25th) percentile of -0.60 (-0.05). From the fact that this distribution is shifted towards negative values (at a $\sim 2\sigma$ level), we argue that most objects have extended radio structure on a subarcsec-scale. Our results strengthen those of Sadler et al.'s (1995) ones, which are based on a smaller Seyfert sample and refer to nuclear components on larger scales ($\sim 1-5$ arcsec), observed with the VLA at 5 GHz. The same authors have already recognized that the inner radio structures of Seyfert galaxies do not look like those of Slee et al.'s (1994) early-type galaxies, where compact radio cores dominate nuclear components on an arcsec scale, observed at 5 GHz with the VLA or the Australian Telescope (AT).

2.9. Radio cores and emission line properties.

Searching for correlations with radio core emission, we consider the measures of $[\text{OIII}]\lambda 5007\text{\AA}$ narrow emission line flux available in the literature, as compiled mostly by de Grijp et al. (1992), Whittle (1992a), Dahari & De Robertis (1988a) (in this order of preference). Besides the fact that line fluxes correlate fairly strongly with F_c , we detect also a weak partial correlation (at the $\sim 93\%$ level) between the corresponding luminosities of all objects (the correlation between $N=50$ detected objects reaches the $\sim 96\%$ level).

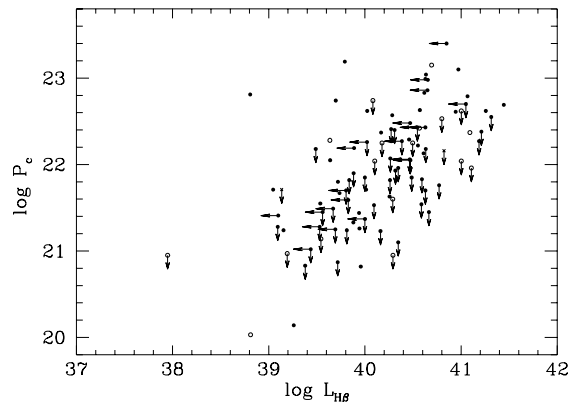


Fig. 6.— The $\log P_c$ - $\log L_{H\beta}$ plot, where P_c is the radio core power (in W/Hz), $L_{H\beta}$ is the luminosity of the $H\beta$ narrow emission line (in erg/s). Symbols as in Figure 2.

Furthermore, we consider the fluxes (or upper limits) of the narrow and broad components of the $H\beta$

emission line as given mostly in the three above-mentioned papers. We detect good partial correlations (at the $\sim 3\sigma$ level) between P_c and the luminosity of the $H\beta$ narrow line, $L_{H\beta}$, for S2 and all objects (although fluxes and uncensored data are unrelated). Table 5 lists the relevant outstanding results of our partial correlation analysis (symbols as in Table 2). Figure 7 shows the $\log P_c$ - $\log L_{H\beta}$ plot for all objects.

Moreover, we consider the $[\text{OIII}]\lambda 5007\text{\AA}$ narrow emission line widths measured at 50% and 20% levels with respect to the peak intensity. We take the former quantity mostly from Nelson & Whittle (1995), Whittle (1992a) and in a few cases from Dahari & De Robertis (1988a) and Vader et al. (1993); for the latter quantity we rely on the compilations by Nelson & Whittle (1995) and Whittle (1992a). We found that the two line width parameters are unrelated to P_c (for $N=63$, $N_{ul}=36$ and $N=43$, $N_{ul}=24$, respectively), even if we drop out E/S0 galaxies or undetected objects.

For S2 objects, where the narrow components of Balmer lines are best determined, we find no correlations between P_c (or F_c) and an indicator of optical excitation such as the narrow line ratio $[\text{OIII}]\lambda 5007\text{\AA}/H\beta$ (for $N=84$, $N_{ul}=29$ upper limits on F_c , $N'_{ul}=6$ upper limits on $H\beta$ flux). Neither did we find correlations between P_c (or F_c) and the ratio $[\text{NII}]\lambda 6583\text{\AA}/H\alpha$ (for $N=72$, $N_{ul}=39$ upper limit on F_c , $N'_{ul}=1$ upper limit on line ratio); almost all the latter ratios are taken from de Grijp et al. (1992).

Strong correlations between the (total or central) radio power, the widths of narrow emission lines and the luminosities of the narrow emission lines (a measure of the power of ionizing photons reaching the NLR) have been known for many years in Seyferts (e.g. Whittle, 1992b, c). Also Seyferts having greater infrared luminosities tend to display broader narrow emission lines (e.g., Veilleux, 1991); the same behaviour is observed in generic samples of luminous infrared galaxies (e.g., Veilleux et al., 1995). Remarkably, Miller et al. (1993) noted that the $[\text{OIII}]\lambda 5007\text{\AA}$ luminosities are more closely related to the radio core than to extended radio powers in a sample of low-redshift ($z < 0.5$) quasars. All these correlations probably arise from interactions of ejected radio plasma with the ambient interstellar medium (e.g., the review by Wilson, 1992).

By outlining the relation between radio core and narrow line emissions, which is essentially driven by

S2s, our study suggests that the energy which powers radio cores is fundamentally linked to the supply of energy for the central UV source which photoionizes the NLR. The absence of correlation between radio core power and narrow line width might be due to small-number statistics.

2.10. Radio cores and interaction strength.

In order to describe the interaction strength on our objects, we consider some parameters defined in the literature:

1. the dimensionless interaction class IAC defined by Dahari (1985) as an integer which grows with the interaction effect on the galaxies as seen projected on the sky. The parameter IAC describes both the degree to which a galaxy looks disturbed and the closeness to a neighbour (if there is a close companion). Dahari (1985) assigned IAC=1 to isolated or symmetric galaxies and IAC=6 to highly distorted galaxies or overlapping objects. Later, many Seyfert galaxies were assigned IAC-values by Dahari & De Robertis (1988a). The value of this IAC parameter is available for 41 objects in common ($N_{ul}=24$).
2. the interaction class (hereafter IAC') defined on a scale 1 to 6 by Whittle (1992) as an indicator of the presence of a companion (relative size and proximity). Unlike the previous parameter, this quantity monitors only possible tidal perturbations by nearby companions and not the degree of morphological disturbance. It is tabulated by Whittle (1992a) and Nelson & Whittle (1995) for 48 objects ($N_{ul}=29$) in common.
3. the disturbance class DC defined on a scale of 1 to 6 by Whittle (1992a) as an indicator of a visible response, either to tidal or to some other perturbation. It is given by Whittle (1992a) and Nelson & Whittle (1995) for 43 objects ($N_{ul}=28$).
4. the perturbation class PC, a more comprehensive parameter, which we define as Maximum (IAC, IAC', DC). It is available for 66 objects ($N_{ul}=39$).
5. the presence of a close companion of a similar redshift (if its redshift is known). We take this kind of information generally from Dahari (1994,1995), Dahari & De Robertis (1988a),

MacKenty (1990), Heisler & Vader (1994), Rafanelli, Violato & Baruffolo (1995), and the catalogue by Lipovetski et al. (1987). This information is available for 91 objects ($N_{ul}=51$). In general the selection of probable physical companions of unknown redshift is based on the amount of magnitude difference and separation between the companion and the main component. Although in most cases different authors agree on the presence or absence of a close companion, there is a serious disagreement in the literature regarding 12 ambiguous cases. We simply subdivide the 90 galaxies (for which this kind of information is available into objects without companions (to which we assign a parameter $INT=0$), objects with companions (denoted by $INT=2$), and ambiguous cases (denoted by $INT=1$).

Employing the five two-sample tests, we find no significant difference in the $\Delta(\log P_c)$ distributions between objects with large (> 3 or > 2) and small (< 4 or < 3) values of the parameters IAC, IAC', DC, PC (although objects with large PC-values of these parameters tend to host slightly more frequently detected radio cores).

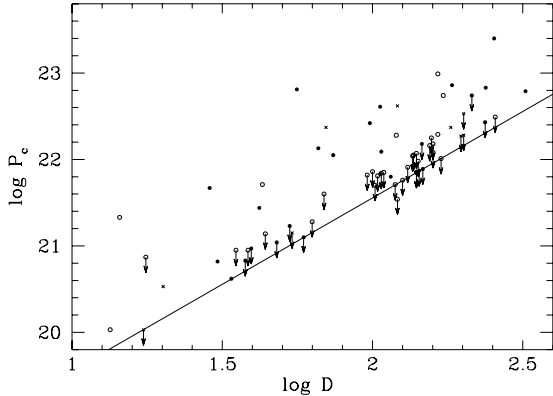


Fig. 7.— The $\log P_c$ – $\log D$ plot (as in Figure 2), but only for non-E/S0 galaxies with some information on the presence of a nearby companion. P_c is the radio core power (in W/Hz) and D is the distance (in Mpc). Different symbols denote galaxies without a companion (open circles), galaxies with a companion (dots), and uncertain cases (crosses). The straight line given by eq. (1) in the text is shown.

On the other hand, galaxies with companions (with $INT=2$) tend to have a $\Delta(\log P_c)$ –distribution slightly shifted to greater values than galaxies without companions (with $INT=0$), with an average statistical significance of $\sim 94\%$. The inclusion of $INT=1$ objects in the $INT=0$ group or in the $INT=2$ group confirms this result with a slightly reduced statistical significance. But, if we exclude E/S0 objects, this effect becomes much stronger ($> 99\%$ significance level) and amounts to a median difference of a factor of ~ 3 in power. Furthermore, we have checked that this effect is not simply due to a slight difference in the S2/S1 number ratio between $INT=0$ and $INT=2$. Table 6 presents the most interesting results. Figure 6 shows the $\log P_c$ – $\log D$ diagram for the non-E/S0 galaxies with $INT=0$ (open circles), $INT=1$ (crosses), and $INT=2$ (dots).

We conclude that radio core activity is favoured by the presence of a close companion, at least in spiral galaxies. Our finding appears to be in line with the results of the VLA radio survey of luminous IRAS galaxies by Neff & Hutchings (1992). They noted that in their sample, which includes also many non-Seyfert galaxies, sources with detected radio cores (of $< 0.8''$ size) reside preferentially in systems with a greater interaction strength, which was established mainly on the basis of morphological disturbances (Hutchings & Neff, 1991). Incidentally, interacting Seyfert galaxies were found to display also enhanced radio emissions from the entire galaxy and from the central ($\lesssim 20''$) region (e.g., Dahari & De Robertis, 1988b; Giuricin et al., 1990).

3. Summary and Conclusions

We may summarize the principal results of our paper as follows:

- 1) The compact radio cores of Seyfert galaxies are characterized by a median power of $\log P_c = 20.9$ (W/Hz) together with a median core-to-total power ratio of 0.17. They are roughly comparable in power with the radio cores observed in the nearest ($z < 0.1$) objects of the Bright Quasar Sample, whilst they appear to be typically weaker than the cores (frequently) detected in early-type galaxies and stronger than the analogous radio structures (rarely) detected in non-Seyfert spiral galaxies.

The radio core power correlates with the total radio power, ($P_c \propto P_T^{1.0 \pm 0.2}$), and the extended radio power ($P_T - P_c$), but it appears to be unrelated to the

structural characteristics of extended radio emission (on an arcsec angular scale), which is not dominated by compact radio cores.

2) Seyfert nuclei hosted in early-type galaxies show a somewhat stronger radio core emission (typically by a factor of ~ 2) than the norm for Seyfert objects. This appears to reflect the general strong association of radio-loud objects with early-type galaxies. Moreover, early-type Seyferts tend to show a slightly flatter P_c - P_T relation ($P_c \propto P_T^{0.8 \pm 0.2}$) than the average for the whole sample. Our results indicate that also within the Seyfert class a connection between radio core activity and galaxy morphology is present (see, e.g., Wilson & Colbert, 1995; Fabian & Rees, 1995 for recent, different interpretations of this connection).

3) Galaxies with a nearby companion (especially non-early-type ones) display enhanced radio core emission with respect to objects without one. This effect, which is in line with the behaviour of extended radio emission, lends further support to the idea that Seyfert activity is stimulated by interactions (e.g. Osterbrok's (1993) review), especially in early-type spirals (e.g., Monaco et al., 1994).

4) Seyfert 2 galaxies are confirmed to have more powerful radio cores (typically by a factor of ~ 1.5) than Seyfert 1. We have verified that this is not due to a different proportion of early types or objects with nearby companions in the two Seyfert classes.

5) Radio core emission is unrelated to optical, near-infrared, far-infrared emissions and ratios of some prominent narrow emission lines. In this respect, the behaviour of the radio core emission appears to be markedly different from that of total and extended radio emission, which well correlate with the optical and far-infrared emissions of the host galaxy.

6) Radio core emission shows some relation with prominent (albeit dissimilar in nature) signatures of AGN activity, such as hard X-ray, mid-infrared (in the IRAS $\sim 12\mu\text{m}$ and $\sim 25\mu\text{m}$ bands), and narrow-line ([OIII] $\lambda 5007\text{\AA}$, $H\beta$) emissions. In this case, the behaviour of radio cores preserves some similarity with that of extended radio power, which is known to be related to the same emissions.

The last results (point 6) suggest that Seyfert radio cores are typically powered by AGNs rather than by radio supernovae, although the power of radio supernovae (e.g., Weiler et al., 1986; Colina & Pérez-Olea, 1992) is comparable with that of the weakest detected radio cores in Seyferts.

Our results (points 1) and 2)) emphasize the difference (Sadler et al., 1995) between Seyfert radio cores and cores of early-type galaxies. On the other hand, a comparison with the compact radio cores observed in nearby QSOs is hardly feasible. Although in many respects the latter structures do not seem identical to Seyfert cores, the discrepancies could be entirely accounted for by differences in spatial resolution and radio survey sensitivity (see, e.g., the end of §2.4 for a discussion of the radio core-optical relation in Seyferts and QSOs). In this respect, we deem it interesting that radio core strength appears to correlate with mid-infrared emission, since mid-infrared, being an approximate constant fraction of the bolometric flux, is believed to provide the best indication of the bolometric luminosity of Seyferts (e.g., Spinoglio & Malkan, 1989; Spinoglio et al., 1995).

Therefore, we suggest that the radio core power is likely to be linked to the bolometric luminosity of Seyfert nuclei, despite the fact that it represents a negligible fraction of the power output of the central engine. This link would assimilate Seyfert radio cores to radio-quiet QSO radio cores, which have recently been claimed to be reliable tracers of the QSO bolometric power output (Lonsdale et al., 1995), which in QSOs, unlike Seyferts (precisely Seyferts 2), is typically dominated by blue and UV radiation.

Besides high-resolution observations at higher frequencies (less affected by free-free absorption), there is a strong need for radio measurements on an arcsec/subarcsec scale for many Seyfert objects. These measurements would probe the connection (if any) between compact radio cores and inner radio structures, for which limited and inhomogeneous information is now available.

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Table 1: Comparisons between the Radio Core Power of Objects of Different Morphologies

| Sample pairs | Variable | N | N_{ul} | $p(G_1)$ | $p(G_2)$ | $p(L)$ | $p(P_1)$ | $p(P_2)$ |
|--------------|------------------|-----|----------|----------|----------|--------|----------|----------|
| E/S0 | | 31 | 15 | | | | | |
| vs | $\Delta(\log P)$ | | | 0.075 | 0.070 | 0.062 | 0.069 | 0.140 |
| S | | 72 | 49 | | | | | |
| E/S0 | | 31 | 15 | | | | | |
| vs | $\Delta(\log P)$ | | | 0.049 | 0.045 | 0.039 | 0.045 | 0.107 |
| S+S/S0 | | 76 | 53 | | | | | |
| E/S0 | | 31 | 15 | | | | | |
| vs | $\Delta(\log P)$ | | | 0.092 | 0.085 | 0.063 | 0.078 | 0.213 |
| S+S/S0+uncl. | | 118 | 78 | | | | | |

Table 2: Correlations between Radio Core Power and Infrared Quantities

| Variables | Sample | N | N_{ul} | N'_{ul} | τ | σ | p |
|----------------------------------|--------|-----|----------|-----------|--------|----------|-------|
| $\log P_c - \log L_N$ | all | 55 | 29 | 3 | 0.025 | 0.045 | >0.10 |
| $\log P_c - \log L_{12}$ | S1 | 54 | 40 | 19 | 0.046 | 0.027 | 0.09 |
| $\log P_c - \log L_{12}$ | S2 | 88 | 47 | 36 | 0.056 | 0.032 | 0.08 |
| $\log P_c - \log L_{12}$ | all | 144 | 89 | 57 | 0.053 | 0.022 | 0.02 |
| $\log P_c - \log L_{25}$ | S1 | 54 | 40 | 7 | 0.008 | 0.029 | >0.10 |
| $\log P_c - \log L_{25}$ | S2 | 88 | 47 | 3 | 0.065 | 0.033 | 0.05 |
| $\log P_c - \log L_{25}$ | all | 144 | 89 | 10 | 0.038 | 0.023 | 0.10 |
| $\log P_c - \log L_{60}$ | all | 144 | 89 | 4 | 0.002 | 0.026 | >0.10 |
| $\log P_c - \log L_{100}$ | all | 144 | 89 | 21 | 0.018 | 0.025 | >0.10 |
| $\log P_c - \log(F_{12}/F_{60})$ | all | 140 | 85 | 53 | 0.058 | 0.025 | 0.02 |
| $\log P_c - \log(F_{25}/F_{60})$ | S1 | 51 | 37 | 4 | 0.020 | 0.048 | >0.10 |
| $\log P_c - \log(F_{25}/F_{60})$ | S2 | 87 | 46 | 2 | 0.079 | 0.036 | 0.03 |
| $\log P_c - \log(F_{25}/F_{60})$ | all | 140 | 85 | 6 | 0.064 | 0.028 | 0.02 |

Table 3: Correlation between Radio Core Power and Hard X-Ray Emission

| Variables | N | N_{ul} | N'_{ul} | τ | σ | p |
|-----------------------|----|----------|-----------|--------|----------|-------|
| $\log P_c - \log L_x$ | 30 | 17 | 2 | 0.144 | 0.062 | 0.021 |

Table 4: Correlation between Core and Total Radio Powers

| Variables | Sample | N | N_{ul} | N'_{ul} | τ | σ | p |
|-----------------------|--------|----|----------|-----------|--------|----------|-------|
| $\log P_c - \log P_T$ | S2 | 44 | 20 | 4 | 0.153 | 0.070 | 0.028 |
| $\log P_c - \log P_T$ | all | 92 | 55 | 13 | 0.076 | 0.037 | 0.041 |

Table 5: Correlation between Radio Core Powers and Emission Lines

| Variables | Sample | N | N_{ul} | N'_{ul} | τ | σ | p |
|------------------------------|--------|-----|----------|-----------|--------|----------|-------|
| $\log P_c - \log L_{[OIII]}$ | all | 130 | 80 | 0 | 0.040 | 0.022 | 0.069 |
| $\log P_c - \log L_{H\beta}$ | S2 | 79 | 41 | 21 | 0.083 | 0.027 | 0.003 |
| $\log P_c - \log L_{H\beta}$ | all | 99 | 56 | 21 | 0.073 | 0.024 | 0.003 |

Table 6: Comparison between the Radio Core Power of Objects with and without Close Companions

| Sample Pairs | Variable | N | N_{ul} | $p(G_1)$ | $p(G_2)$ | $p(L)$ | $p(P_1)$ | $p(P_2)$ |
|-----------------------|------------------|----|----------|----------|----------|--------|----------|----------|
| INT=0 | | 47 | 32 | | | | | |
| vs | $\Delta(\log P)$ | | | 0.083 | 0.081 | 0.038 | 0.062 | 0.056 |
| INT=2 | | 32 | 13 | | | | | |
| Without E/S0 galaxies | | | | | | | | |
| INT=0 | | 34 | 27 | | | | | |
| vs | $\Delta(\log P)$ | | | 0.009 | 0.008 | 0.004 | 0.005 | 0.005 |
| INT=2 | | 27 | 11 | | | | | |

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